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Experimental and numerical investigations on flame stability of methane/air mixtures in mesoscale combustors filled with fibrous porous media

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ABSTRACT

Flame stability of methane/air mixtures in mesoscale channels with different diameters (6 mm, 5 mm and 4 mm) filled with fibrous porous media was experimentally investigated. Standing combustion waves (namely, stationary flame) are observed under low inlet velocity and high equivalence ratio conditions. Moreover, the standing wave regime becomes narrower as the channel diameter is reduced from 6 mm to 5 mm and vanishes for the 4-mm channel. For a fixed equivalence ratio, the flame length becomes shorter at a smaller channel or a less inlet velocity. Regarding the downstream propagating wave, its propagation velocity increases with the decrease of channel diameter. Splitting flame appears at large inlet velocities. Besides, at low equivalence ratios, the downstream propagating flames grow into small flame balls and can survive until the channel exit. Numerical results demonstrate that for a smaller channel, although the total heat loss rate is reduced, its heat loss ratio is increased, which leads to a lower wall temperature level and the flame is quenched out near the wall. The combustion efficiency is decreased significantly for the 4-mm channel due to fuel leakage from the near-wall "dead space".

1. Introduction

Extensive attention has been drawn on microscale and mesoscale combustion in the past decades due to the rapid development of micro-electromechanical systems [1]. As the combustor dimension is reduced, the heat loss ratio increases and the residence time of gaseous mixture decreases drastically. As a result, the flame is prone to various instabilities in small channels [2].

A variety of flame stabilization techniques have been implemented to anchor the flame in microscale and mesoscale combustors. Swiss-roll configuration was applied to miniature combustors for flame stabilization and the flame blow-off limit was experimentally investigated [3]. Moreover, it was found that for the Swiss-roll combustors turbulence models can achieve better predications than the laminar model [4]. The flame blow-off limit can be significantly extended due to heat recirculation effect of the preheating channel [5]. The impacts of inner/outer reactor heat recirculation on the characteristics of a microscale combustion system were studied by Bagheri and Hosseini [6]. A micro-combustor with a backward facing step for micro-thermophotovoltaic power generators was developed by Yang et al. [7]. The effects of geometric parameters on the system performance were studied [8]. A micro-scale bluff-body combustor was designed and a very large flame blow-off limit was obtained [9]. The effect of solid materials, i.e., quartz, stainless steel (SS), and silicon carbide (SiC) on the blow-off limit of this micro-combustor was numerically investigated [10]. The impact of bluff-body shape on the flame blow-off limit was further examined [11]. Numerical investigations on the combustion characteristics of methane (CH_4) and air mixtures in a micro-combustor with a hollow hemispherical bluff-body was conducted by Zhang et al. [12]. A micro-combustor with dual cavities was developed for CH_4/air combustion [13]. Although large flame blow-off limits can be obtained in this kind of combustor, "flame tip opening" phenomenon occurs for lean hydrogen (H_2) and air mixtures, which leads to a sharp drop in the combustion efficiency [14]. The micro cavity-combustor with a moderate gap distance was found to has a higher combustion efficiency of lean H_2/air flames [15]. The same non-monotonic tendency of combustion efficiency versus the wall thermal conductivity was observed in this micro combustor [16]. However, the effect of external surface emissivity on the combustion efficiency was shown to be monotonic [17]. Recently, a micro-combustor with four cavities was developed and its wall temperature profile was demonstrated to be more uniform compared to that with only two cavities [18].

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Porous ceramic of high conductivity was adopted in microscale combustion for a micro thermophotovoltaic system and a more uniform wall temperature distribution was obtained [19]. Standing wave regimes of premixed H_2/air combustion in planar micro-combustors partially filled with porous medium were experimentally studied by Li et al. [20]. A self-thermal insulation miniature combustor was developed by Jiang et al. [21], which can reduce the heat loss and sustain the flame in the combustion chamber. The behaviors of CH_4/air flames in mesoscale quartz tubes filled with ceramic fibers were investigated [22]. This type of porous medium is soft, light, and has a high porosity and a low thermal conductivity. A standing wave regime which covers a wide range of equivalence ratio and inlet velocity was obtained in this fibrous medium. Later, a further numerical study on the combustion in this fibrous porous media was conducted by Fursenko et al. [23]. Recently, dynamic characteristics of CH_4/air flames in the 8-mm channel filled with ceramic fibers were numerically investigated by Liu et al. [24]. They also explored the effect of wall thermal conductivity on stability and combustion efficiency of CH_4/air flames in this mesoscale channel [25]. It was shown that the standing wave regime became narrower and the combustion efficiency is decreased as the wall thermal conductivity was increased.

The main objectives of the present work are to experimentally and numerically investigate the scale effect on the flame stability (such as the area of standing combustion wave and flame propagation speed) and combustion efficiency in channels of even smaller inner diameter ($d < 8$ mm) filled with fibrous porous media. Another purpose is to find out the approximate critical diameter under which the stationary flame can no longer sustain. First, experiments were conducted to obtain the flame stability diagram in quartz tubes of $d = 6$ mm, 5 mm and 4 mm. Then, numerical simulations were performed to analyze the impact of channel diameter on the standing wave regime and combustion efficiency.

2. Experimental method

The mesoscale channels are three quartz tubes of different inner diameters (i.e., $d = 6$ mm, 5 mm and 4 mm). The total length (L) and thickness (δ) of the channels are 200 mm and 1 mm, respectively. A ceramic fiber with an average diameter of 2.65 μm is adopted as the porous media, as shown in Fig. 1a. The main chemical constituents of this ceramic fiber are aluminium oxide (Al_2O_3: 40%), silicon dioxide (SiO_2: 58.1%) and chromium oxide (Cr_2O_3: 1.8%). Detailed thermal properties of the porous media and tube wall are: $\varepsilon = 0.92$, $\rho_s = 2600$ kg/m^3, $c_s = 850$ kJ/(kg K), $\lambda_s = 0.03$ W/(m K), $k_s = 0.8$, $\rho_w = 2650$ kg/m^3, $c_w = 750$ kJ/(kg K), $\lambda_w = 1.05$ W/(m K), $k_w = 0.92$. Here, ε, ρ, c, λ and k are the porosity, density, specific heat, thermal conductivity and emissivity, respectively. The subscripts "s" and "w" stand for porous media and quartz tube, respectively. To assure the porosities are almost the same for the three channels, we can control the masses of ceramic fibers that stuffed into the tubes based on the definition of porosity.

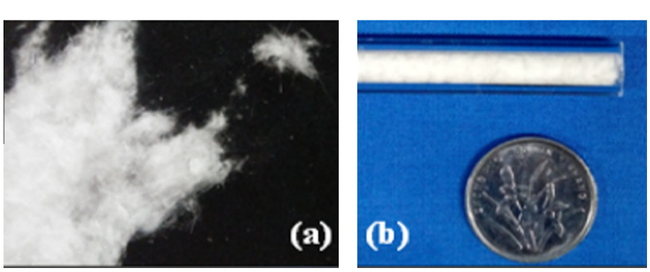

Fig. 1. Direct photos of the fibrous porous media (a) and packed tube.

$$\varepsilon = 1 - \frac{m/\rho_s}{V} \tag{1}$$

$$m = (1 - \varepsilon)\rho_s V \tag{2}$$

Here, ρ_s is the density of ceramic fibers, V is the volume of the tube and m is the mass of the ceramic fiber that should be filled in the tube. The mass is measured with an electronic balance. In addition, patient and careful operation is necessary to assure the fibers are uniformly filled (Fig. 1b). The experimental results reported below are repeatable.

The experimental system is schematically shown in Fig. 2. CH_4 and air of high pressure were stored in two gas tanks. Their pressures were reduced to atmospheric pressure and they were fully mixed before entering into the channel. The inlet velocity (V_{in}) and equivalence ratio (ϕ) of the gaseous mixture were controlled by two electric mass-flow meters with an accuracy of 1% over the full range. A flash-arrester was installed in the fuel line for the sake of safety. A butane/air torch was used to ignite the CH_4/air mixtures with a constant equivalence ratio (0.6–1.0) by heating the tube wall at a fixed position 40 mm away from the channel inlet. In the experiment, a digital camera was applied to take flame photographs with an exposure time of 1/400 s and an exposure compensation value of −1.7. A ruler made of stainless steel was placed in parallel with the mesoscale channel. The flame propagation processes were recorded by a video camera and the flame propagation velocity can be obtained.

3. Experimental results

According to the main purposes of this study, the overall flame stability diagram, direct photos of various flame propagation modes, and flame propagation velocity were experimentally obtained, which will be presented in following subsections.

3.1. Flame stability diagram

Fig. 3 depicts the flame stability diagram under different inner diameters of the channel. It is seen from Fig. 3 that there are three regimes according to the combustion wave behaviors: extinction, downstream propagation and standing wave. For $d = 5$, 6 mm, when $\phi > 0.7$, the standing combustion wave can be observed if the inlet velocity is relatively lower. With a further increment in the equivalence ratio, the upper and lower limits of inlet velocity for this regime are extended. For example, for $d = 5$ mm, the inlet velocity range of standing wave is 0.16–0.20 m/s at $\phi = 0.8$, while it extends to 0.14–0.22 m/s at $\phi = 0.9$. As the inlet velocity is

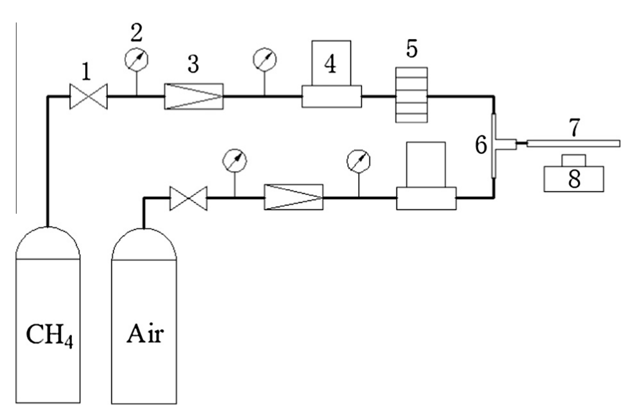

Fig. 2. Schematic diagram of experimental system: 1. Manual valve; 2. Pressure gauge; 3. Pressure reducing valve; 4. Mass flow controller; 5. Flash arrester; 6. Mixer; 7. Mesoscale channel.